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COSMIC NEUTRINOS AND THEIR DETECTION

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COSMIC NEUTRINOS AND THEIR DETECTION. Although it was quite obvious from the basic work of Bethe and Critchfield on hydrogen reactions in stars that stellar neutrinos were produced abundantly in nature, only recently have attempts been made to detect them and other cosmic neutrinos. One of the obvious reasons for this is the smallness of the cross section in neutrino interactions (the cross section is $\sim 10^{-44}$ cm^2 at 1 mev neutrino energy). In lead, the mean free path of 1 mev neutrino is one light year ($\sim 10^{18}$ cm). Recent developments in the theoretical and experimental aspects of the weak interaction have made it possible to study cosmic neutrinos, including stellar neutrinos.

Neutrino Interactions. The present theory of weak interactions originated from Feynman and Gell-Mann. They postulated that the weak interactions were caused by the interaction of a current J with itself. The current has the following form:

$$J = \sqrt{g}[(\Psi_e \gamma_a (1+\gamma_5)\Psi_{\nu_e}) + (\Psi_p \gamma_a (1+\gamma_5)\Psi_n) + (\Psi_\mu \gamma_a (1+\gamma_5)\Psi_{\nu_\mu}) + \text{strange particles}] \qquad (1)$$

where ψ_A is the wave function for a particle A, γ_α (α = 1,2,3,4) are the Dirac Matrices and $\gamma_5 = i\gamma_0\gamma_1\gamma_2\gamma_3$, g is the weak interaction coupling constant and numberically $gm_p^2 = (1.01 \pm 0.01)\times10^{-5}$ (m_p is the mass of proton). The neutrino ν_e associated with electrons is distinguished from that associated with the μ-meson (ν_μ). That $\nu_e \neq \nu_\mu$ has been demonstrated in a recent experiment by Danby *et al*.

We may abbreviate J as follows:

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$$J = (e\nu_e) + (pn) + (\mu\nu_\mu) + \ldots\ldots \qquad (2)$$

where e, ν_e , ... now stand symbolically for particles or anti-particles. The weak interaction Hamiltonian is then given by

$$JJ^* = (e\nu_e)(\overline{e}\overline{\nu}_e) + (pn)(\overline{e}\overline{\nu}_e) + \ldots\ldots \qquad (3)$$

Each term in JJ^* now gives rise to a reaction consistent with all conservation laws (charge, lepton number, energy, momentum, etc.). For example, some of the allowable reactions of the first two terms in Eqn.(3) are

$$e^{\pm} + \nu_e, \overline{\nu}_e \rightarrow e^{\pm} + \nu_e, \overline{\nu}_e \quad \text{(Scattering of neutrinos by electrons)}$$

$$e^- + p \rightarrow n + \nu_e \quad \text{(electron capture)}$$

$$n \rightarrow p + e^- + \overline{\nu}_e \quad \text{(neutron decay)} \qquad (4)$$

At present an experiment at CERN (and a similar one at Brookhaven National Laboratory) is underway to test a new hypothesis in weak interactions (on the existence of an intermediate boson) from which the validity of the theory of Feynman and Gell-Mann could be established. Preliminary results support their theory.

Neutrino Production Associated with Stellar Nuclear Processes. Neutrinos are produced through the $(e\nu_e)(pn)$ interaction of Eqn.(3) in hydrogen reactions in which helium is built up. There are two energy production cycles, the proton-proton reaction is important in stars less massive than the sun, and the carbon cycle is more important in the other case. In all cases the temperature required is around 1 - 3x10^7 $^{\circ}$K. The proton-proton reaction chain is

$$p + p \rightarrow D + e^+ + \nu_e$$
$$D + p \rightarrow He^3$$
$$He^3 + He^3 \rightarrow He^4 + 2p \qquad (5)$$

As helium is built up in the center, the following bi-cycle may take place:

$$He^3 + He^3 \rightarrow Be^7 + \gamma$$
$$Be^7 + e^- \rightarrow Li^7 + \nu \quad (E_\nu = 0.861 \text{ mev}, \ 0.383 \text{ mev})$$
Line Spectra
$$Li^7 + p \rightarrow Be^8 + \nu$$
$$Be^8 \rightarrow 2He^4 \qquad (6)$$

or:

$$Be^7 + p \rightarrow B^8 + \gamma$$
$$B^8 \rightarrow Be^8 + e^+ + \nu \quad (E_\nu^{(max)} = 16.96 \text{ mev})$$
Continuous Spectra
$$Be^8 \rightarrow 2He^4 \qquad (7)$$

The last reaction is of particular interest to neutrino astronomers since these neutrinos have higher energy and should be easier to detect.

The carbon cycle is:

$$C^{12} + p \rightarrow N^{13} + \gamma$$

$$N^{13} \rightarrow C^{13} + e^{+} + \nu_e \quad (E_\nu^{(max)} = 1.2 \text{ mev}) \text{ Continuous Spectra}$$

$$C^{13} + p \rightarrow N^{14} + \gamma$$

$$N^{14} + p \rightarrow O^{15} + \gamma$$

$$O^{15} \rightarrow N^{15} + e^{+} + \nu_e \quad (E_\nu^{(max)} = 1.74 \text{ mev}) \text{ Continuous Spectra}$$

$$N^{15} + p \rightarrow C^{12} + He^{4} \qquad (8)$$

Note C^{12} acts as a catalyst.

The total energy release in building up one helium nucleus from four protons is 26.7 mev, about 0.52 mev to 1.7 mev are in the form of neutrinos. Hence we can say generally in hydrogen burning stars about 2 % to 8 % of energy radiated is in the form of neutrinos.

Table I lists the flux intensity expected on the earth.

TABLE I

Solar Neutrino Fluxes on Earth (ν/cm²-sec)

	ν_{pp}	ν_{Be}		ν_B	ν_N	ν_D
Spectrum type	continuous	line		continuous	continuous	continuous
Maximum energy (mev)	0.42	0.383 12%	0.861 88%	14.06	1.20	1.74
Mean energy (mev)	0.26	---	---	7.25	0.710	1
Flux	$(5.3\pm0.6) \times 10^{10}$	$(1.2\pm0.5) \times 10^{10}$	1.5×10^{9}	$(2.5\pm1) \times 10^{7}$	$(1\pm0.5) \times 10^{9}$	$(1\pm0.5) \times 10^{9}$

ν_{ppe} = neutrino from $p + p + e^{-} \rightarrow D + \nu$, etc.

Very small amounts of neutrinos are produced in association with nuclear energy generations in later stages of stellar evolution. Almost all neutrinos produced at a later stage come from direct production processes.

Direct Neutrino Production Processes. Of all astrophysical processes for neutrino production, the more important ones are:

URCA process

$$\left.\begin{array}{l} e^- + (Z, A) \rightarrow (Z-1, A) + \nu_e \\ (Z-1, A) \rightarrow (Z, A) + e^- + \overline{\nu}_e \end{array}\right\} \text{beta decay interaction} \qquad (9)$$

Photo neutrino process

$$e^- + \gamma \rightarrow e^- + \overline{\nu}_e + \nu_e \qquad (10)$$

Annihilation process

$$\gamma + \gamma \rightleftharpoons e^- + e^+ \rightarrow \overline{\nu}_e + \nu_e \qquad (11)$$

(e ν)(e ν) interaction

Plasma process

$$\gamma\ (\text{plasmon}) \rightarrow \overline{\nu}_e + \nu_e \qquad (12)$$

The URCA process is at present of historical importnace, since it was the first one to be considered. In the URCA process beta decay and inverse beta decay reactions occur alternatively, depleting the kinetic energy of the electrons. This process requires a minimum electron energy roughly equal to the beta decay energy. Since the beta decay energy E_b of most stable nuclei is of the order of a few mev, and the kinetic temperature of the electrons hardly exceeds a few tenths of mev, the Boltzmann factor exp ($- E_b/kT$), which is a measure of the fraction of the number of electrons with energy $> E_b$, is rather small and this process is not very important. Moreover, elements with small E_b are not stable against photodisintegration at the temperature when the calculated energy conversion rate becomes large.

In the photoneutrino process the energy of a photon is converted into a pair of neutrinos. This is quite analogous to the Compton scattering process. In the annihilation process the photons are in equilibrium with electron pairs (at a temperature $\sim 6 \times 10^9$ $^{\circ}$K) and the electron pairs can annihilate to form neutrinos via the $(e\nu_e)(e\nu_e)$ interaction.

Ordinarily a free photon cannot decay into two neutrinos because of the conservation laws. Inside an electron gas, because of interactions, photons are not free. The relation between the frequency ω of a photon and its wave number vector k is similar to that for a particle with a mass $\hbar\omega_o$.

$$\hbar^2 \omega^2 = h^2 \omega_o^{\;2} + k^2 c^2$$

whereas

$$\omega_o^{\;2} = \frac{4}{\hbar^2} e^2 p_F^{\;3} \frac{1}{\pi E_F}$$

and p_F is the Fermi momentum for electrons. E_F is the Fermi energy including the rest energy mc^2. Hence inside an electron gas a photon can decay into two neutrinos. The plasma process is expecially important in dense stars (such as white dwarfs and neutron stars).

Detailed calculation of the energy conversion rate on these processes have been performed by Chiu, Stabler, Ritus, Adams, Ruderman, and Woo. The detailed computation is quite complicated. We here list the asumptotic formulae for certain limiting cases.

TABLE II

Summary of Photo neutrino and Annihilation Energy Loss Rates

(ρ in g/cm^3, $T_n = T/10^n$)

Temperature and density region: $c = k = 1$	Photo neutrino Loss (ergs/g-sec)	Pair Annihilation Loss (ergs/g-sec)	Plasma Process (ergs/g-sec)
Non-relativistic, non-degenerate $E_F \lesssim T \ll m$	$\frac{10^8}{\mu_e} T_9^8$	$\frac{4.8\times10^{18}}{\rho} T_9^3\, e^{-2mc^2/kT}$	$\frac{\hbar\omega_o}{kT} >> 1$
Extreme relativistic, non-degenerate $m \ll T,\ E_F \lesssim T$	$\frac{2.5\times10^{14}}{\mu_e} T_{10}^{\,8}(\log_{10}T_{10} + 1.6)$	$\frac{4.3\times10^{24}}{\rho} T_{10}^{\,9}$	$1.5\text{x}10^{22}\left(\frac{\hbar\omega_o}{mc^2}\right)^{7.5}\left(\frac{mc^2}{kT}\right)^{-1.5}\exp\left(-\frac{\hbar\omega_o}{kT}\right)$
Non-relativistic, extreme degenerate $T \ll E_F < m$	$1.5\times10^2\, T_8 \left(\frac{1}{\mu_e}\right)^{2/3}\frac{1}{\rho^{1/3}}$	$4.5\times10^6\, T_8^{\,3/2}\mu_e \exp\left[\frac{-(2mc^2+E_F)}{kT}\right]$	$\frac{\hbar\omega_o}{kT} << 1$
Extreme relativistic, extreme degenerate $T,\ m \ll E_F$	$\frac{6.3\times10^6}{\mu_e}(1+5T_9^2)T_9^7 \frac{m}{E_F}{}^{3}$	$\frac{1.4\times10^{11}}{\mu_e} T_9^4 \left(\frac{E_F}{m}\right)^2 \exp(-E_F/T)$	$2.96\text{x}10^{22}\left(\frac{\hbar\omega_o}{mc^2}\right)^6\left(\frac{mc^2}{kT}\right)^{-3}$

<u>Nucleosynthesis Beyond Hydrogen Burning. Supernova.</u> As hydrogen becomes exhausted at the center of a star, a dense helium core develops and the star becomes a red giant, with a vast envelope.

Because of gravitational contraction, the temperature at the center increases, and at T ~ 10^8 °K helium begins to react via the $3\alpha \rightarrow C^{12}$ reaction.

At a temperature of around 4×10^9 °K, nuclear reaction rates become quite rapid, as a consequence all elements come to statistical equilibrium and the most favored element is Fe^{56}. At a temperature of around 8×10^9 °K, the equilibrium configuration changes to He^4. This change is endothermic. Also, the neutrino processes we discussed previously also dissipate stellar energy quickly. With these two endothermic reactions the star contracts rapidly and collapses. The result is a supernova.

In Figure 1 we plot the neutrino luminosity L_ν of a star as a function of its central temperature. At T > 5×10^8 °K, the energetics of a star are entirely governed by neutrinos. Overall, roughly 25 % of stellar energy is released in the form of 1 mev neutrinos.

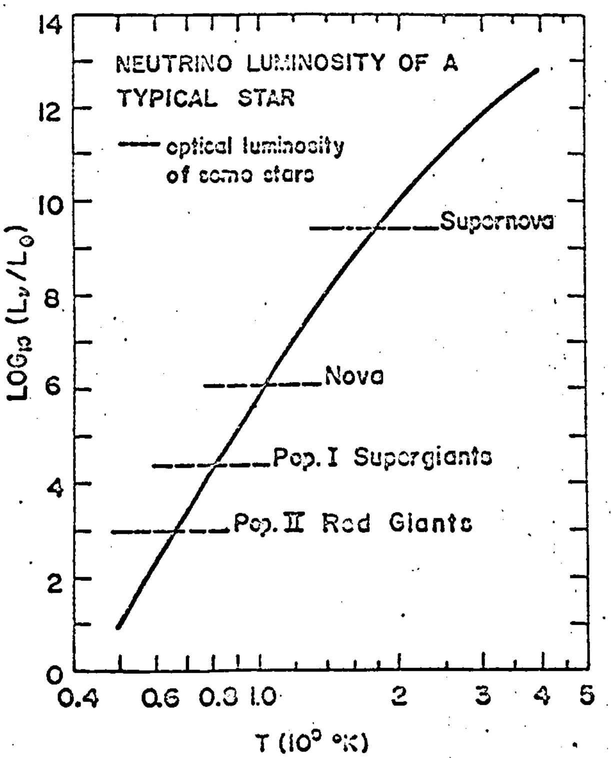

FIGURE 1.

$L_\odot$ is the solar energy output rate = 4×10^{33} ergs/sec

In Table III we list the neutrino history of a star.

TABLE III

Neutrino History of a Star

The Average life time is taken to be 3×10^9 years, the total optical energy output is taken to be 3×10^{50} ergs.

Stage	$<E_\nu>$ (mev)	Total Energy (ergs)	Duration (years)
Main Sequence (Hydrogen burning) (Beta process)	0.26	10^{49}	3×10^9
	0.8	4×10^{49}	3×10^9
	7.	4×10^{44}	3×10^9
Red giant (Helium burning and plasma process)	10 kev	10^{47}	10^8
Late stages (pre-supernova, photo-neutrino and pair annihilation processes)	100 kev → 1 mev	10^{50}	10^4 very rapidly
	URCA process 2.58 mev		
Supernova explosion and collapse	100 mev	up to 10^{54}?	a fraction of a second?
	Very uncertain	Numbers vary, depending on who speculates	
White dwarfs (plasma process)	1 → 10 kev	$\sim10^{43}$	$10^8 \sim 10^9$

As a star collapses to become a supernova, more high energy neutrinos of energy $\gtrsim$ 100 mev (e and μ type) may be emitted. Rough estimates indicate that energy up to 10^{53} ergs or more may be dissipate in the form of μ-neutrinos. These neutrinos may be detected by using gigantic neutrino detectors to monitor future supernova explosions in our galaxy.

<u>Cosmic Ray Secondary Neutrinos</u>. When primary cosmic rays hit the upper atmosphere, nuclear reactions take place in which π-mesons are created. These π-mesons subsequently decay into μ-mesons and neutrinos (μ type). Because π-mesons produced in the horizontal direction travel in the tenuous upper atmosphere for a longer time, thus reducing the probability to interact strongly with the atmosphere, cosmic ray secondary neutrinos (and μ-mesons) show an anisotropy, favoring the horizontal direction. The flux of these neutrinos is the same as cosmic ray μ-meson flux. The flux is too low to be detected directly.

However, a detector embedded in earth may detect secondary μ-mesons produced by neutrino reactions. These μ-mesons also favor the horizontal direction. Plans are being made to detect these underground secondary μ-mesons.

Table IV lists cosmic neutrino fluxes for different ranges

TABLE IV

Cosmic Neutrino Fluxes

$\langle E_\nu \rangle$	Flux on Earth (ν/cm^2-sec)	Energy Density ev/cm^3	Detectability	Solar Back-ground flux
1-10 kev	10^{5-7}	$10^{-3} \rightarrow 10^{-1}$	no at present	none
0.26 mev	10^6	1	no at present	4×10^{12}
0.8 mev	up to 10^6	1	yes, but difficult	10^{11}
1 mev (ν_e and $\bar{\nu}_e$)	vary rapidly with time	1 on the average	yes, but difficult	10^{11}
7 mev	up to 10^2	10^{-3}	Yes, but solar background must be eliminated (going to Pluto?)	10^7
100 mev	$\sim10^{-4}$	?	yes	none
>1 Bev, cosmic secondaries	same as μ flux	not meaningful to define	yes	none

Solar Neutrinos and Their Detection. The flux of solar neutrinos is big enough for terestial detection at the present status of neutrinology. Pontecovo has suggested that the reaction

$$Cl^{37} + \nu_e \rightarrow A^{37} + e^- \qquad \text{(Threshold 0.8 mev)}$$

$$A^{37} \rightarrow Cl^{37} + e^+ + \bar{\nu}_e \qquad \text{(Half life 30 days)}$$

may be used to detect solar neutrinos. The A^{37} atom may be chemically separated from Cl^{37} (prepared as a liquid carbon tetrachloride CCl_4) by using carriers (He^4), afterwards A^{37} is separated from He^4 by absorption at low temperature ($\sim 20^{\circ}$ K). The half life of A^{37} limits the integration time to around 30 days. This method has been put into practice by Raymond Davis. A total amount of 0.5×10^6 liters of CCl_4 will be needed, and the daily production rate of A^{37} is around 10 atoms. (The natural abundance of C^{37} is 25 %.)

J. N. Bahcall pointed out that transitions occuring between the ground state of Cl^{37} $Cd_{3/2}$, J = 3/2+, T = 3/2) and the excited state of A^{37} J = 3/2+, T = 3/2 (5.1 mev) is superallowed and a cross section at 10 mev neutrino energy of around 0.8×10^{-42} cm^2 may be expected. The size of the cross section is a large determinary factor for the feasibility of solar neutrino astronomy.

Conclusion. Stellar neutrinos are produced abundantly and in the future neutrino astronomy may be expected to play an important role in our study of the cosmos.

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